

## LA-UR-21-25404

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Title: Nuclear Materials Production & Technical Nuclear Forensics

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Intended for: Virtual presentation to the University of Texas

Issued: 2021-06-09

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# Nuclear Materials Production & Technical Nuclear Forensics

## Intelligence & Systems Analysis Group (A-2)



Mark Scott

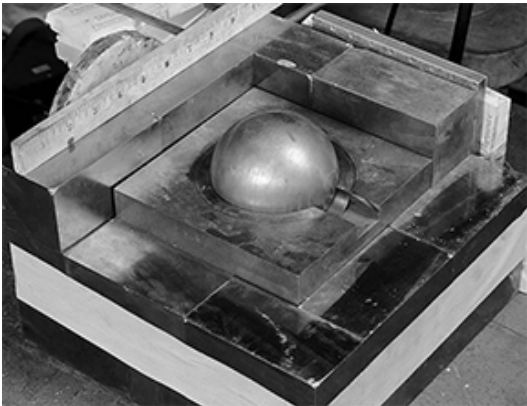
2021



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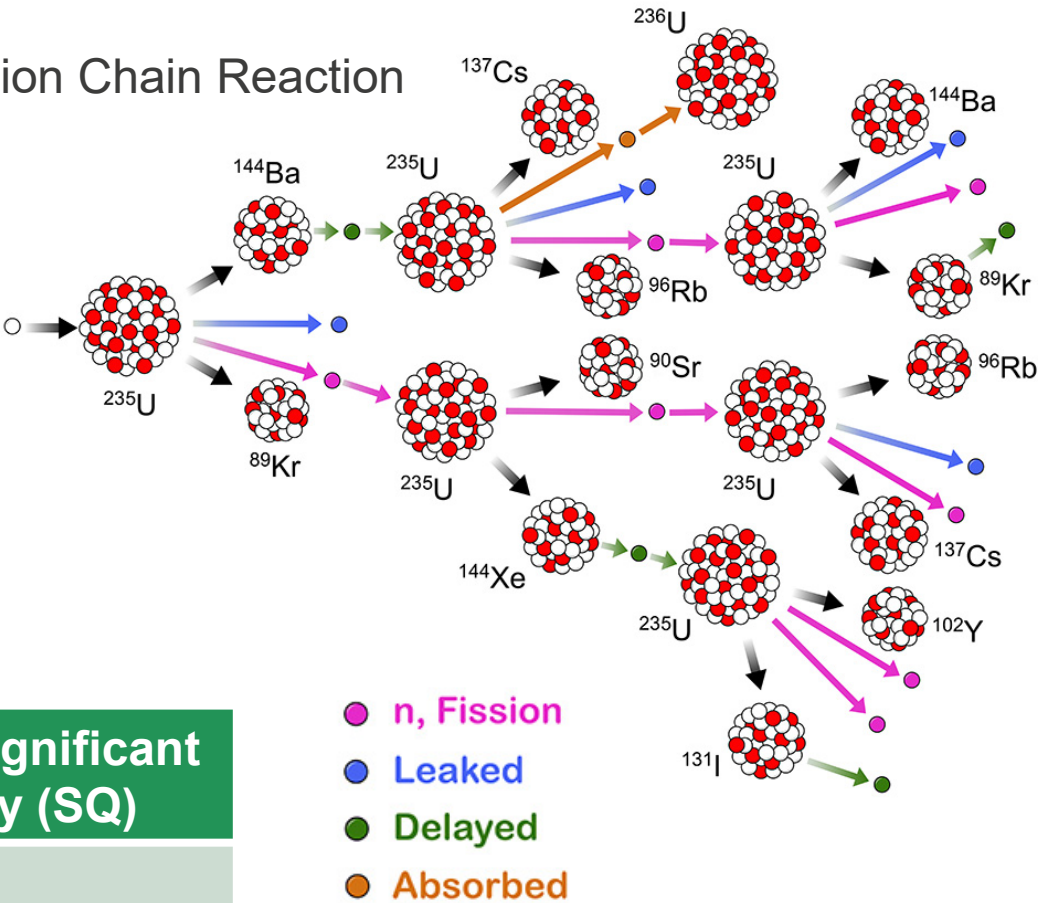
Unclassified

# Fundamentals of a Nuclear Fission Chain Reaction



Demon Core

Fission Chain Reaction



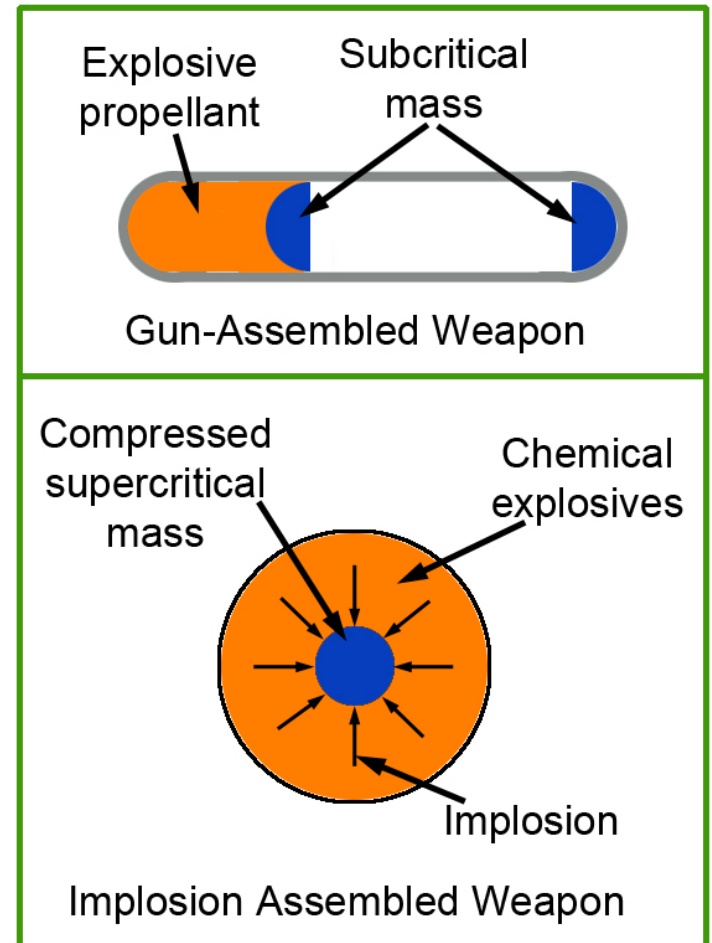
Critical Mass

Isotope	Bare Sphere Critical Mass	IAEA Significant Quantity (SQ)
$^{235}\text{U}$	52 kg	25 kg
$^{239}\text{Pu}$	10 kg	8 kg

# Pathways to a Nuclear Weapon

To create a nuclear weapon you must first obtain weapons grade material.

- Enriched uranium
- Plutonium



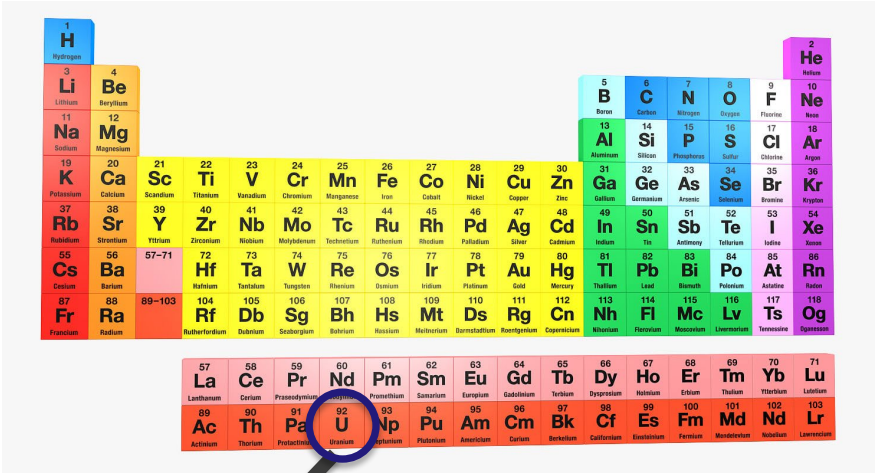
# Hurdles to Manufacturing an Improvised Nuclear Device (IND)

**What is the primary hurdle to manufacturing an IND?**

## **Obtaining Weapon-Usable Nuclear Material (WUNM)**

- **First Line of Defense (FLD):**
  - Securing WUNM at civilian and defense facilities against theft and/or diversion.
- **Second Line of Defense (SLD):**
  - Building radiation detection capacity in partner countries to enhance border control to deter, detect and interdict WUNM.
- **International Nonproliferation Export Control Program (INECP)**
  - To prevent the illicit procurement of equipment, materials, and technological know-how to develop weapons of mass destruction (WMD).

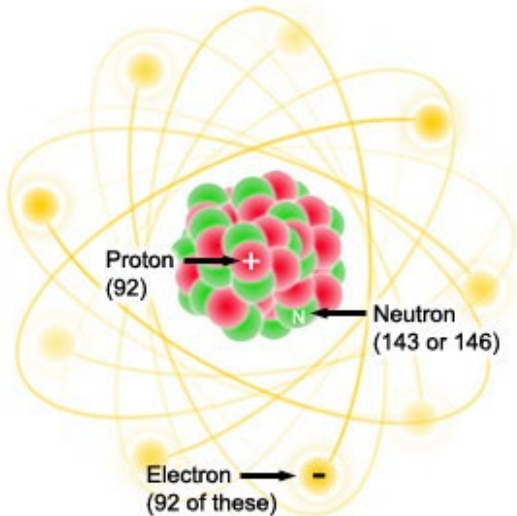
# Uranium Isotopes



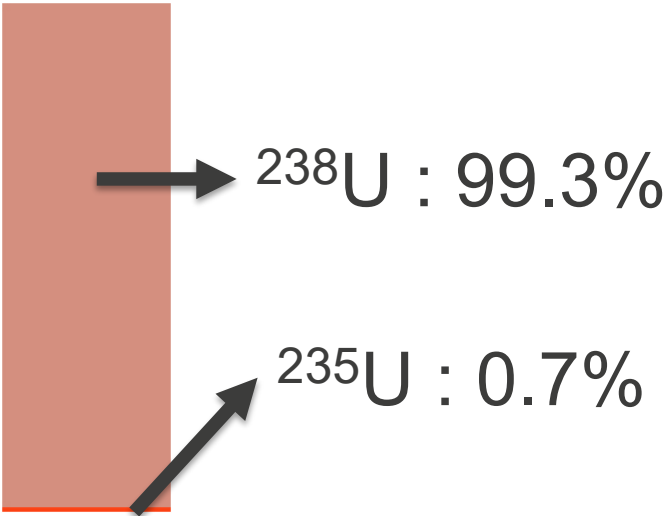
92

U

Uranium

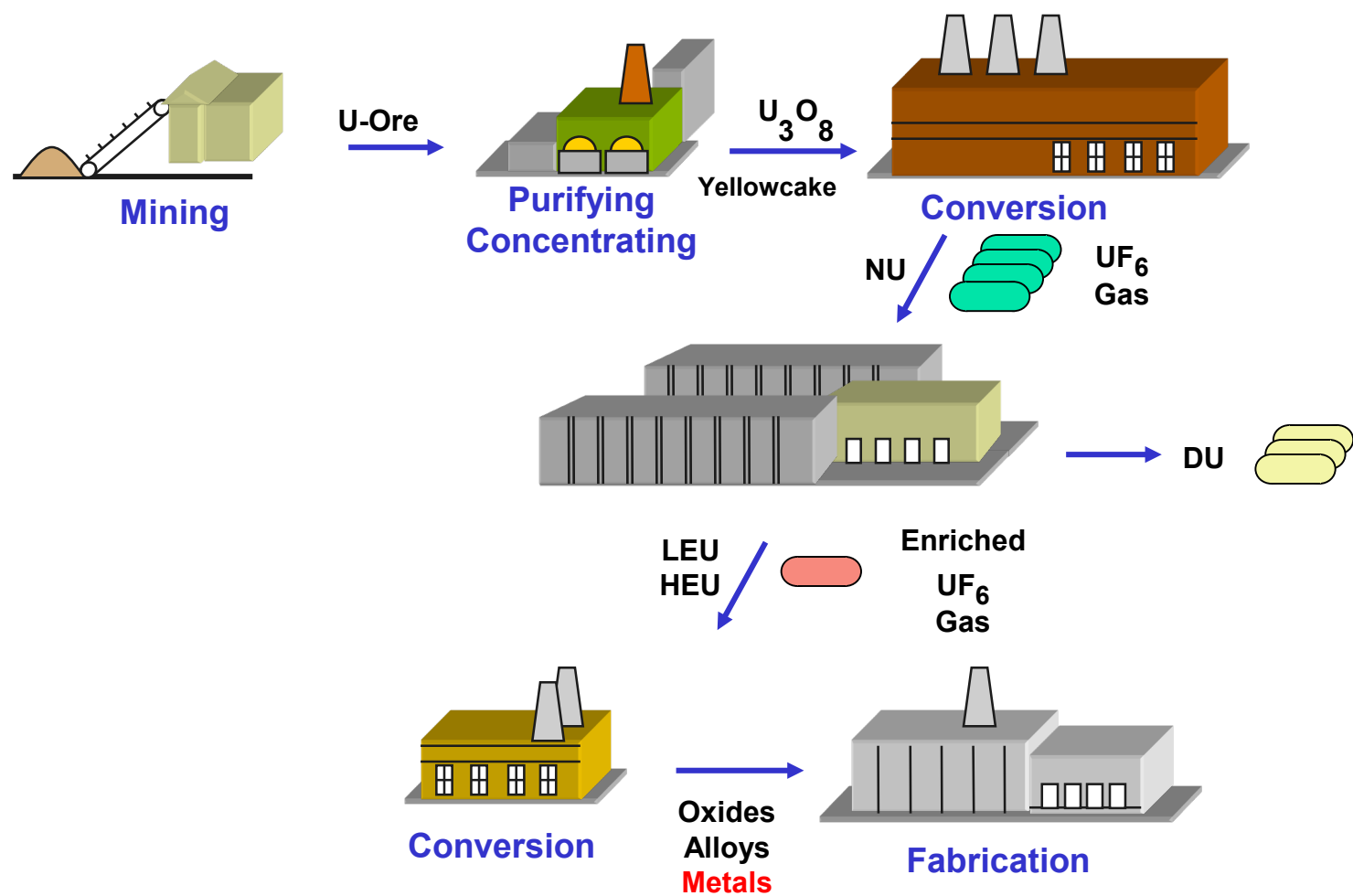


## Natural Uranium



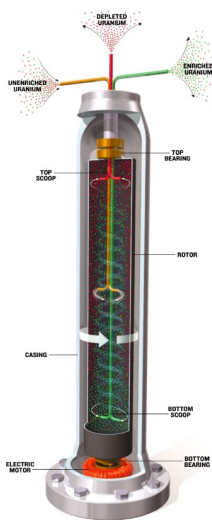
U-235	Acronym	Description
<0.7	DU	Depleted U
0.7	NU	Natural U
0.7 – 20	LEU	Low Enriched U
>20	HEU	Highly Enriched U
>90		Weapons Grade

# Enriched-U Production

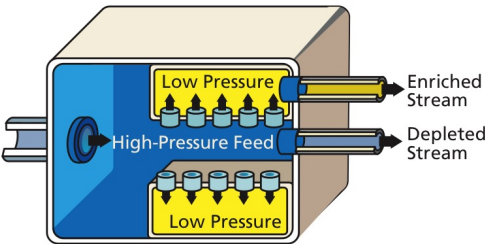


# Uranium Enrichment Techniques

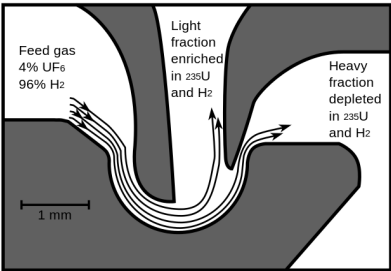
## Gas Centrifuge



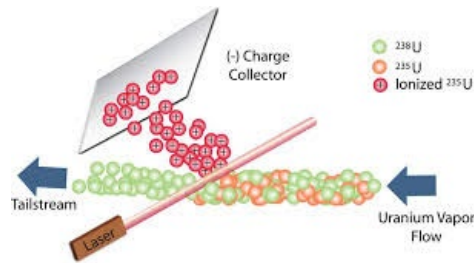
## Gaseous Diffusion



## Aerodynamic Nozzle

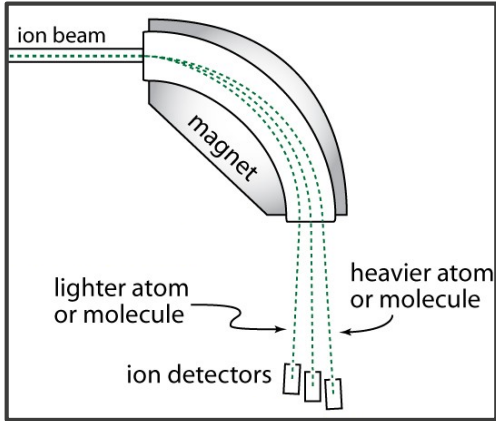


## Laser Enrichment AVLIS, MLIS, SILEX



- Alternative Methods**
- Chemical (CHEMEX)
  - Plasma
  - Thermal (Oak Ridge)

## EMIS or Calutron

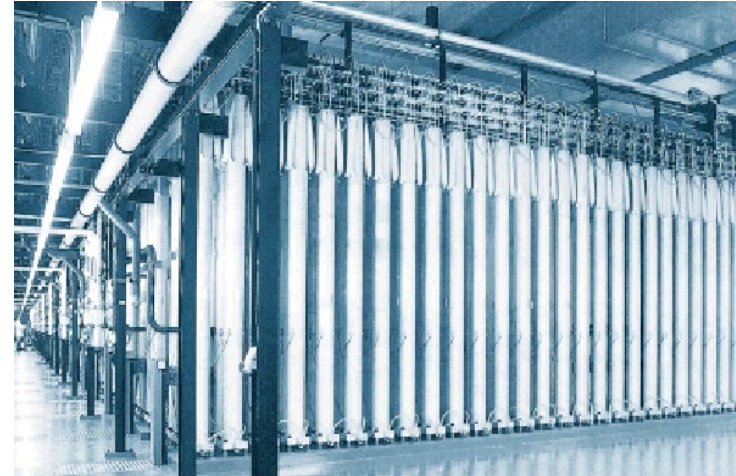


# Comparison of Gaseous Diffusion & Centrifuge

## Gaseous Diffusion



## Centrifuge



- High pressure – High thru-put
- Operates as Single Cascade
- 1000 stages: natural  $\rightarrow$  3.5%  
4000 stages; natural  $\rightarrow$  90%
- 100-300 sq. ft. per stage
- $\sim$  2,500 kW hr/SWU
- Extract 25x more energy out

- Low pressure – Low thru-put
- Multiple Cascades
- 10's- 100 stages: natural  $\rightarrow$  3.5%  
300 - 1000 stages: natural  $\rightarrow$  90%
- 6-8 sq. ft. per stage
- $<$  50 kW hr/SWU
- Extract 1500x more energy out

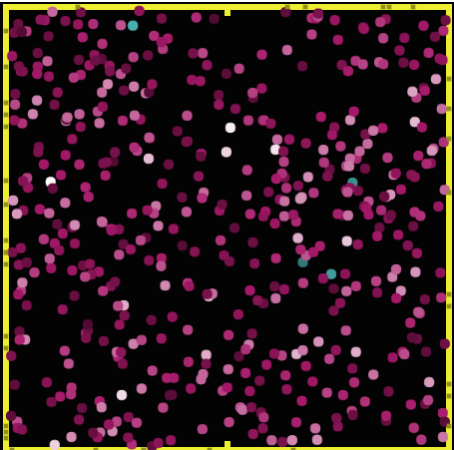
# Visualizing U-235 Enrichment

- U-238 Atoms
- U-235 Atoms

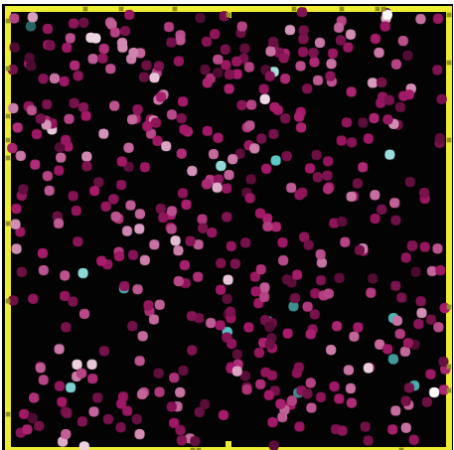
Feed	Product	Centrifuges*
0.7%	20%	96
20%	90%	15

\*40 SWU/year per centrifuge

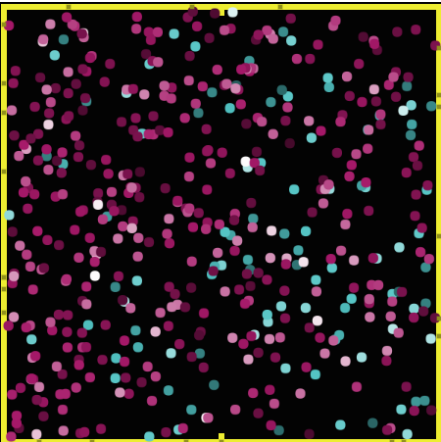
0.71% U-235



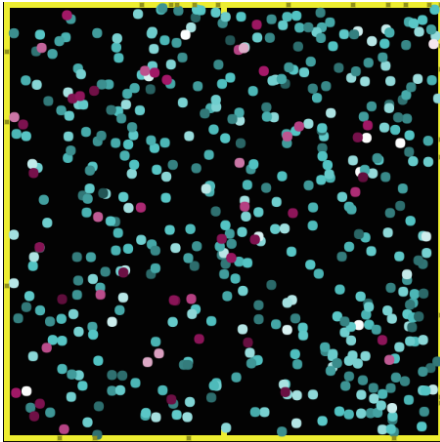
3.0% U-235



20% U-235



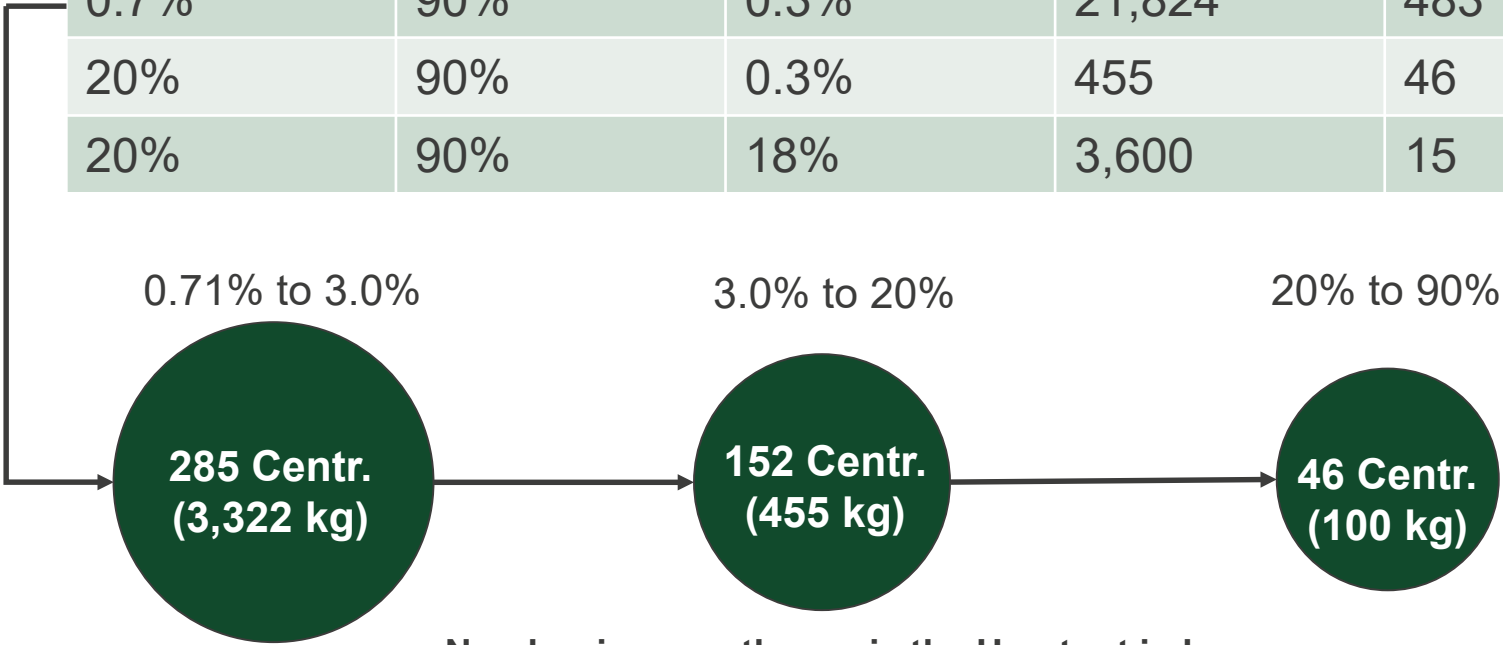
90% U-235



# Centrifuges to Produce HEU from LEU

Centrifuges to produce 100kg of product per year

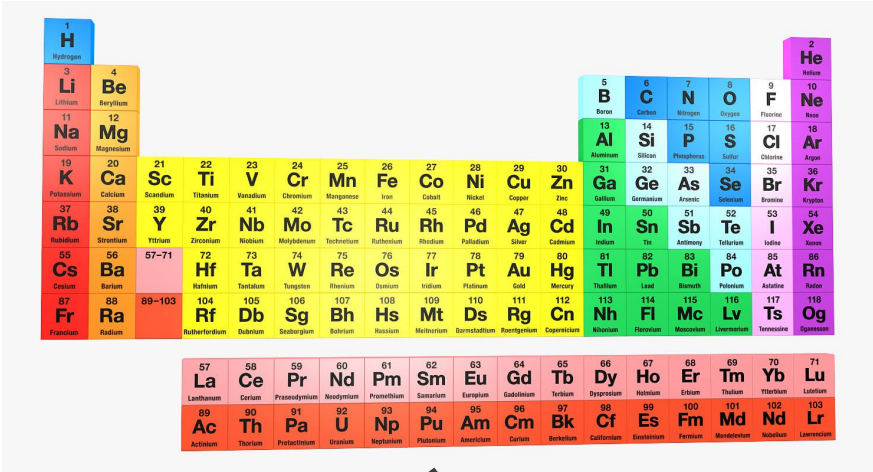
Feed U-235	Product U-235	Tails U-235	Feed Mass (kg)	Centrifuges 40 SWU/year
0.7%	90%	0.3%	21,824	483
20%	90%	0.3%	455	46
20%	90%	18%	3,600	15



Number in parentheses is the U output in kg

A Westinghouse 1,000 MWe PWR reactor has a core load of 66,410 kg of uranium fuel between 2.1% – 3.1% U-235

# Uranium Isotopes



94

Pu

Plutonium

## Production:



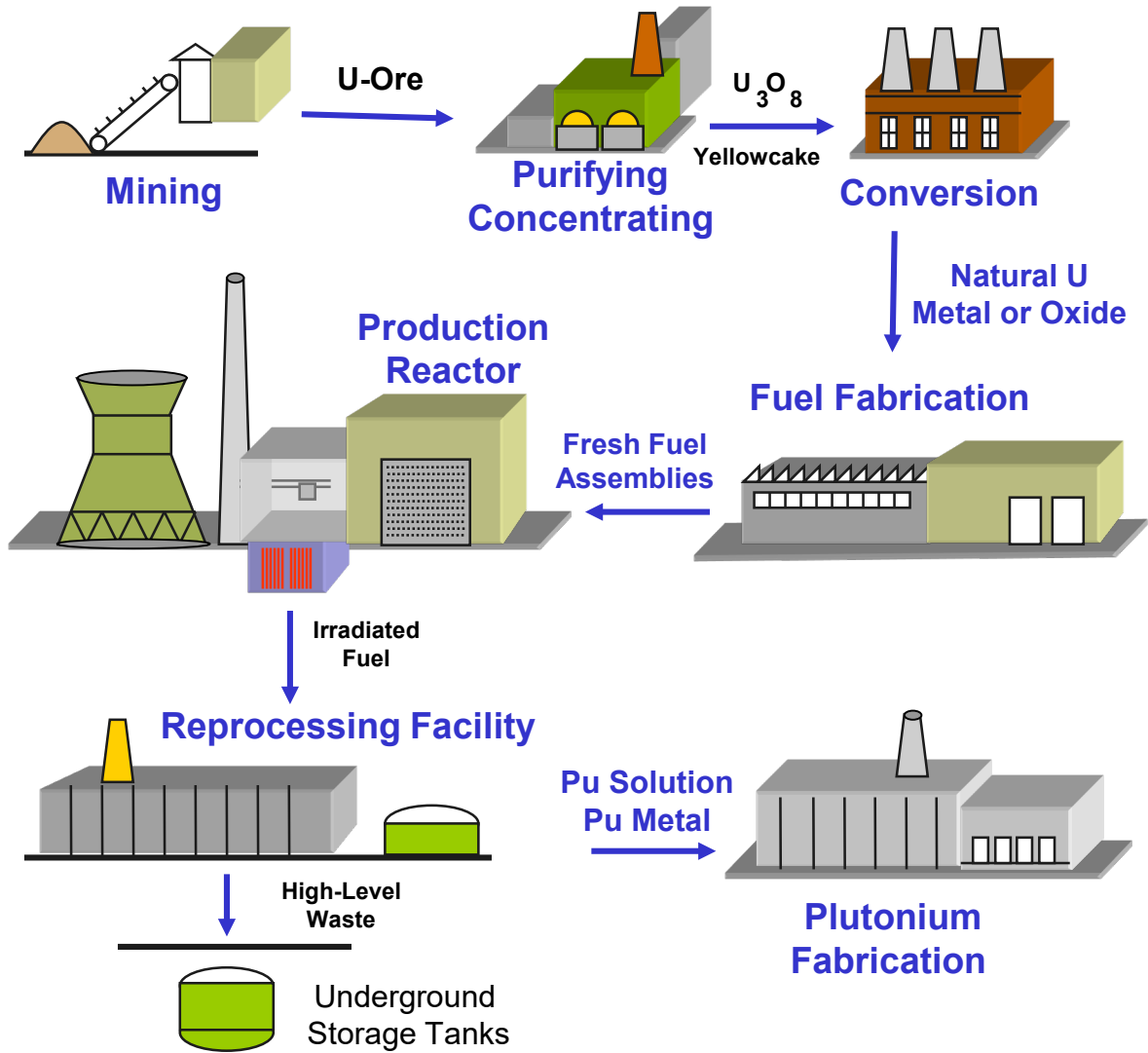
## Conversion:



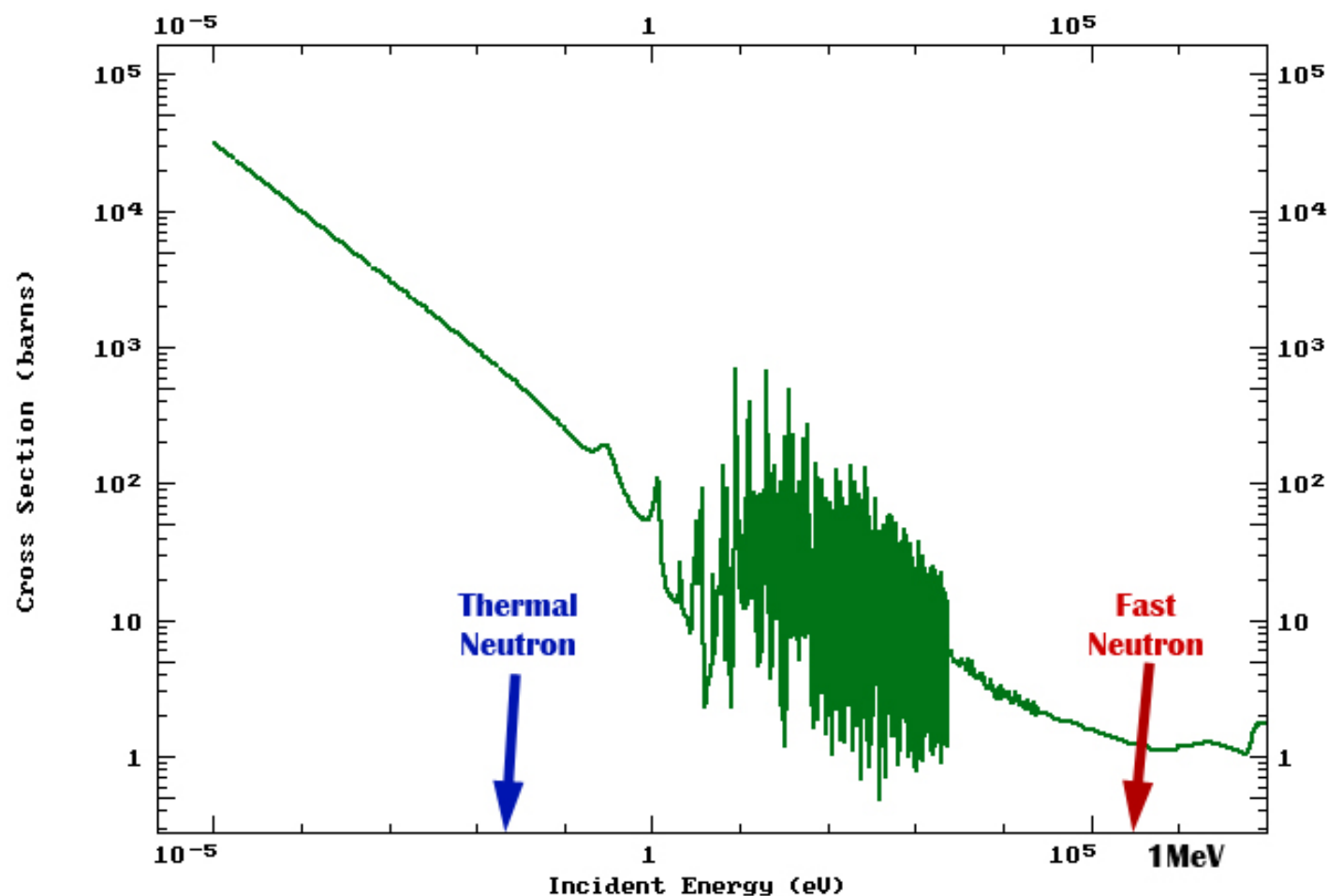
Pu-240 %	<1976	>1976
<7	Weapons Grade	
7-19	Reactor Grade	Fuel Grade
>19		Reactor Grade

(Significant Quantity of Pu-239: 8kg)

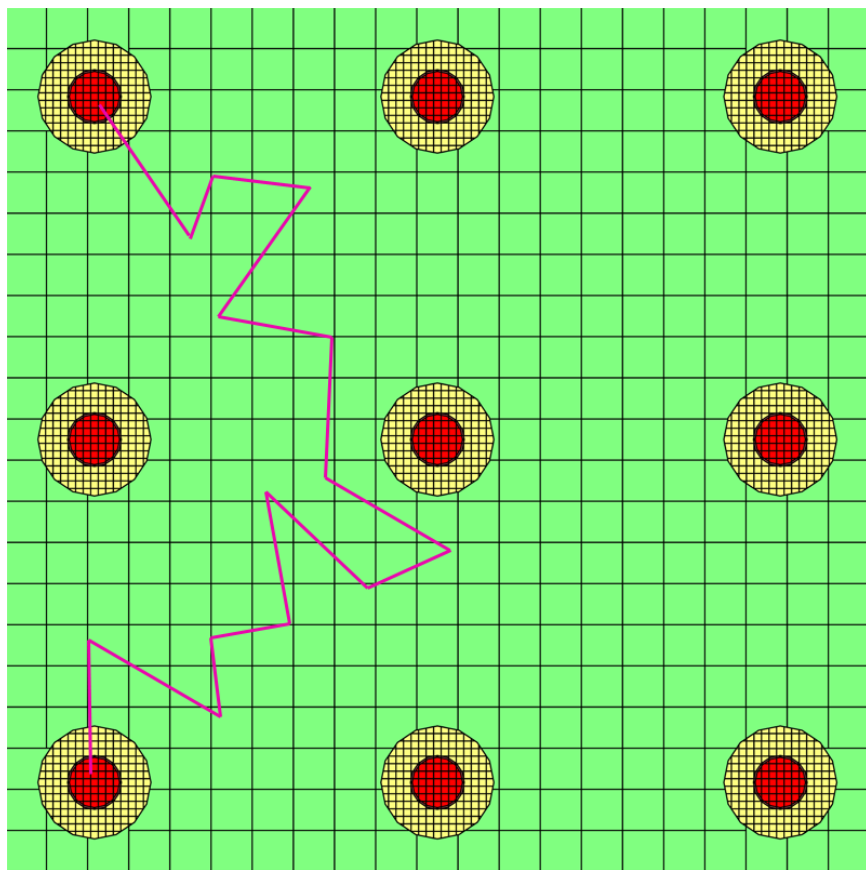
# Plutonium Production



# U-235 Neutron Fission X-Section

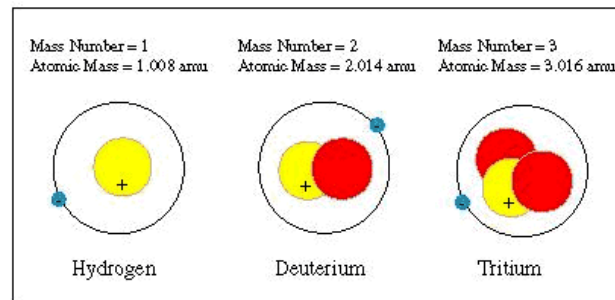


# Moderation of Fast Neutrons



On average water ( $\text{H}_2\text{O}$ ) will moderate a neutron after 16 collisions.

Heavy water ( $\text{D}_2\text{O}$ ) requires approximately 29 collisions to moderate a neutron.



*Hydrogen isotope diagram from NASA JPL*

# Classes of Reactors

Reactor Class	Moderator	Coolant	Fuel
Light Water (PWR, BWR, VVER)	Water	Water	LEU
Heavy Water (CANDU, PHWR)	Heavy Water	Water	Natural
Graphite (gas) (MAGNOX, AGR)	Graphite	CO <sub>2</sub>	Natural
Graphite (water) (RBMK, Hanford)	Graphite	Water	LEU/Nat.

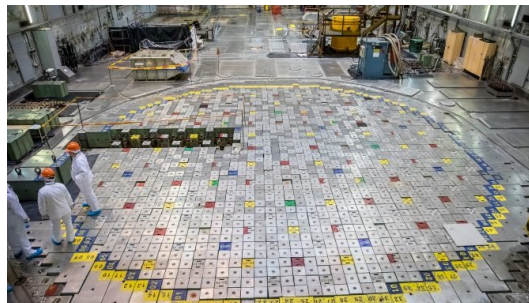
Other Reactor Types: TRIGA, PBR, Fast, SMR, MSR, AHR

PWR at Cape Town, SA



Pic: Koeberg nuclear power station, Cape Town, South Africa. Credit: Bjorn Rudner

RBMK at Ignalina, LT



CANDU at Bruce Power

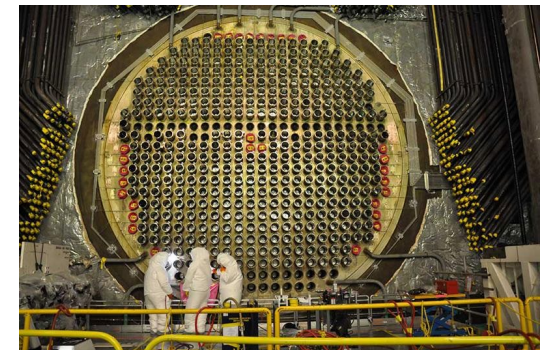


Photo: Bruce Power/Cameco Corp.

# Pu Production – Rules of Thumb

## Typical production rate:

0.91 g-Pu/MWd - Graphite Reactor

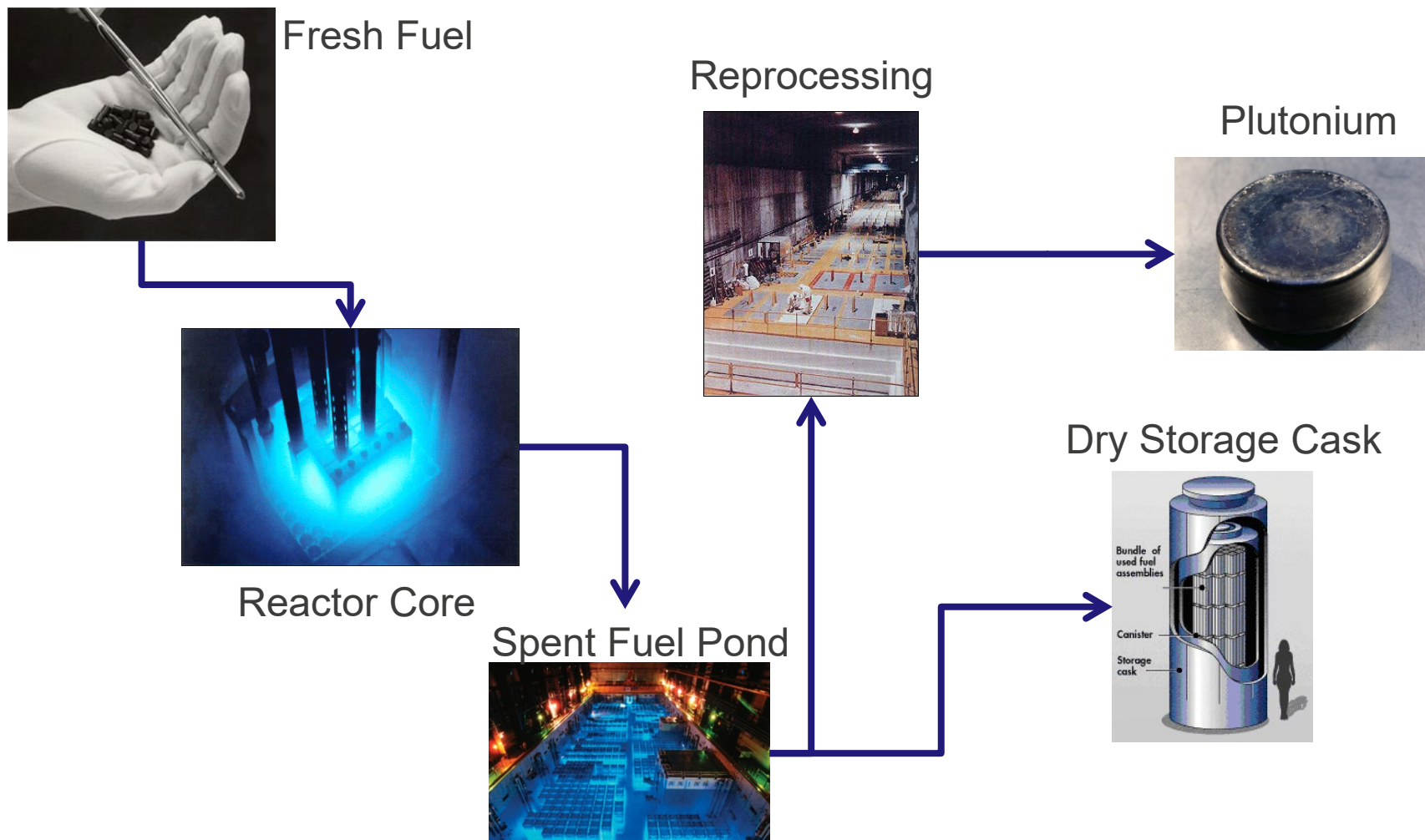
1.2 g-Pu/MWd - Heavy Water Reactor

Reactor Type	% U-235 Fuel	Typical Burnup (GWd/MTU)	Pu / MTU	% Pu-240
Graphite	0.7%	1.2 – 6.0	1.1 – 3.3 kg	3.8 – 28%
CANDU	0.7%	5 – 10	3.0 – 4.5 kg	21 – 31%
PWR	1.5% – 5.0%	15 – 60	5.6 – 13 kg	13 – 26%
BWR	1.1% - 3.5%	10 – 60	4.0 – 12.5 kg	11 – 31%
TRIGA	20%*	80 – 130	8.5 – 12 kg**	14 – 19%
TRIGA	93%*	80 – 130	1.5 – 2.2 kg**	5 – 7.5%

\* TRIGA enrichment is 20, 70 and 93%

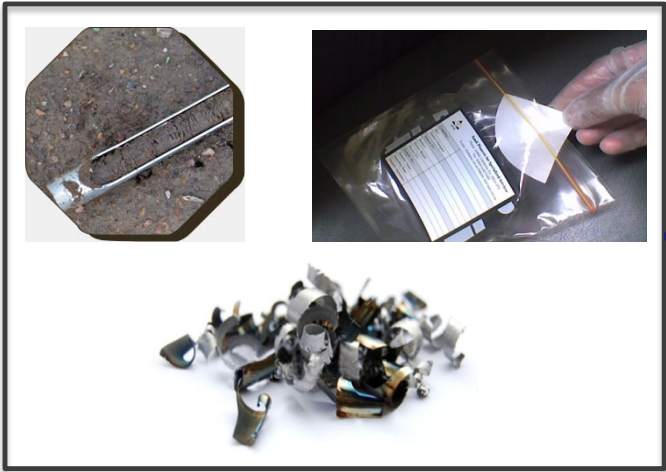
\*\*TRIGA core load is around 2.5 kg of U-235

# Nuclear Reactor Fuel to Separated Plutonium



# Sample Collection

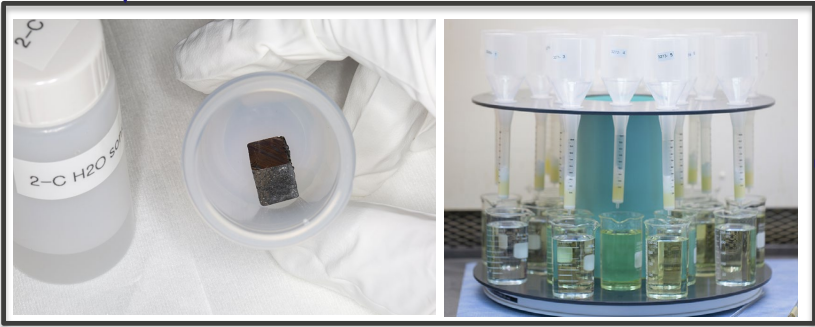
Sample Collection



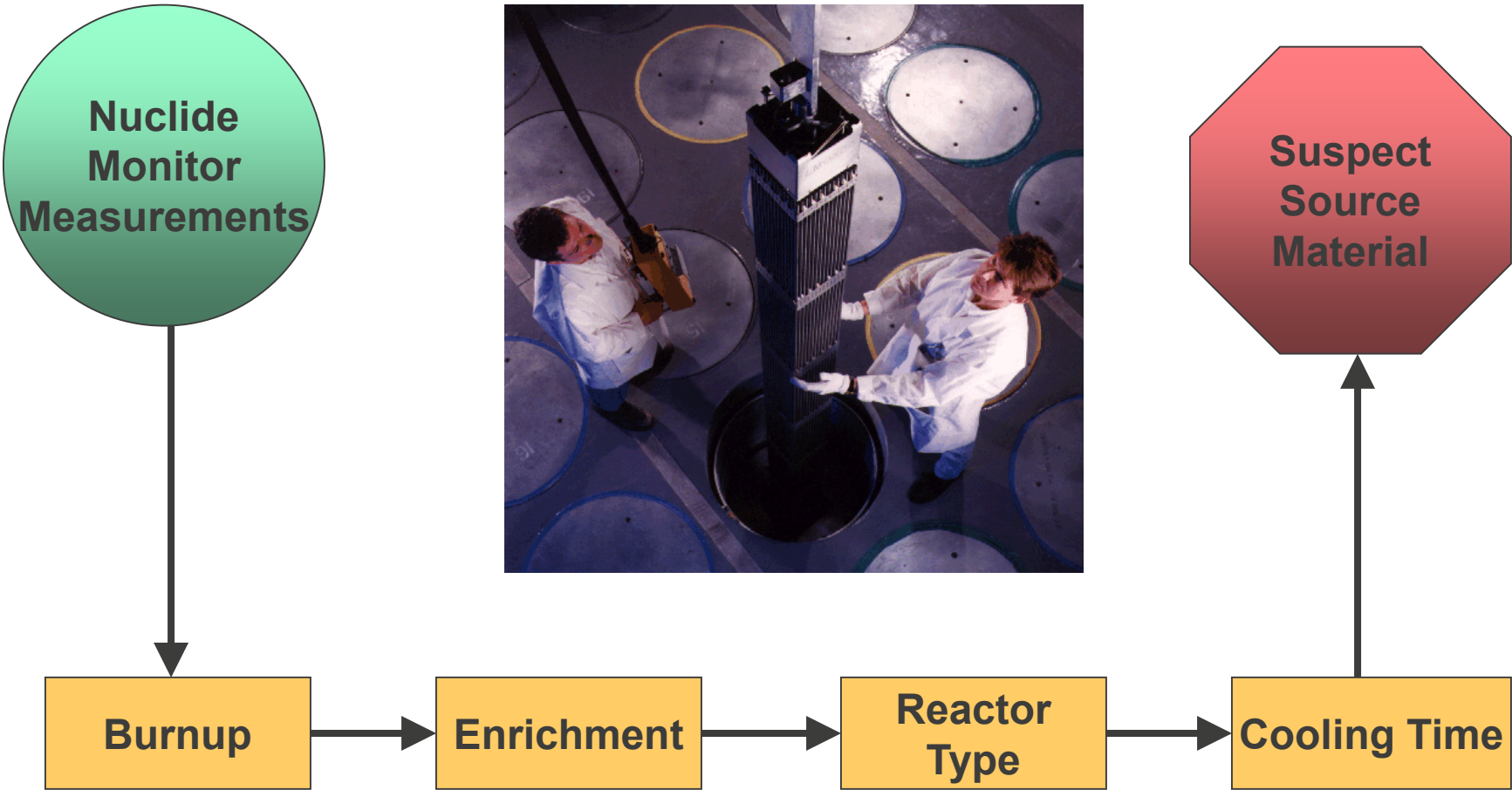
Data Interpretation

U-235	0.56%
U-236	0.03%
U-238	99.41%
Pu-239	87.93%
Pu-240	10.86%
Pu-241	1.11%
Pu-242	0.07%

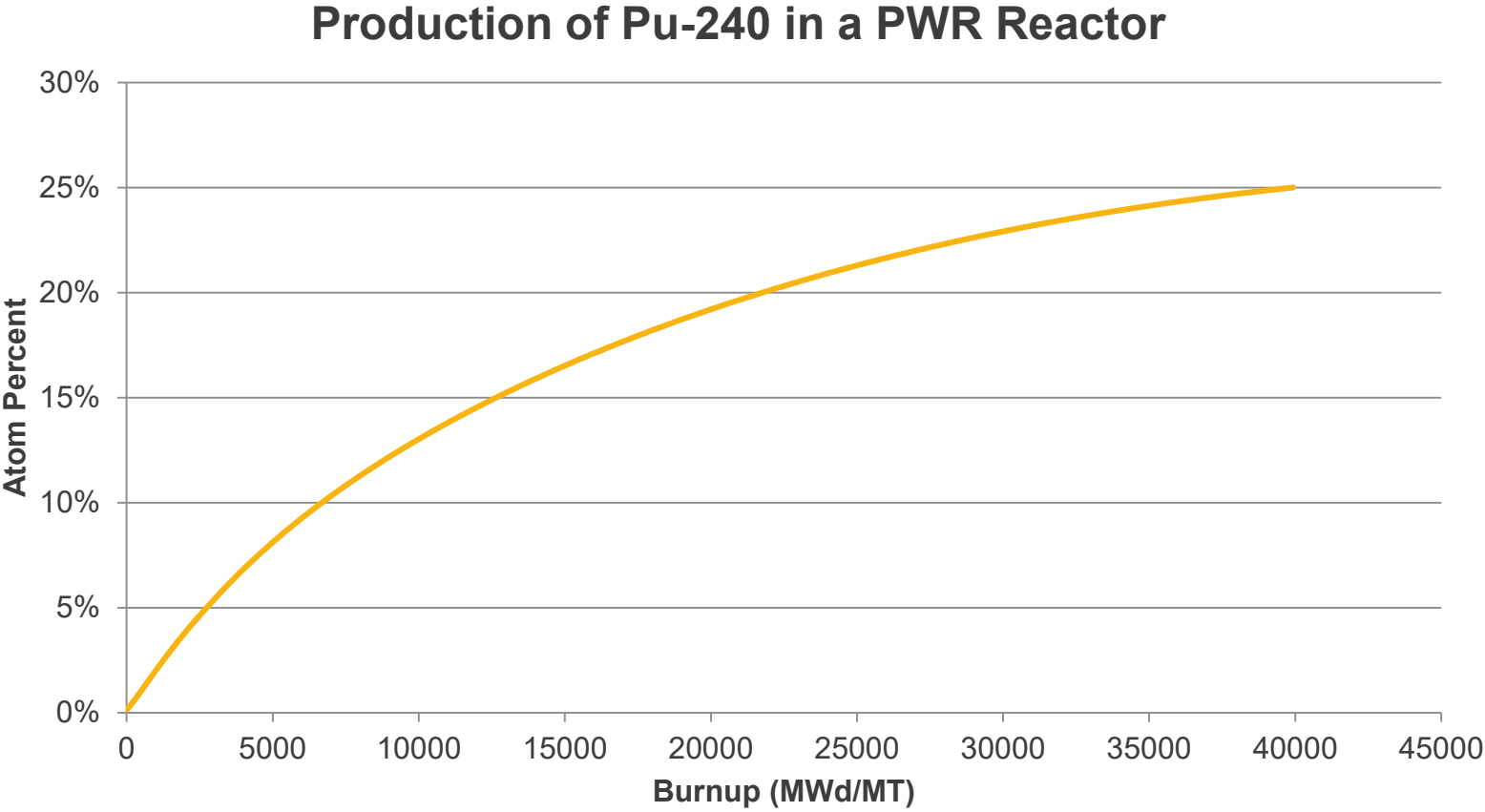
Laboratory Analysis



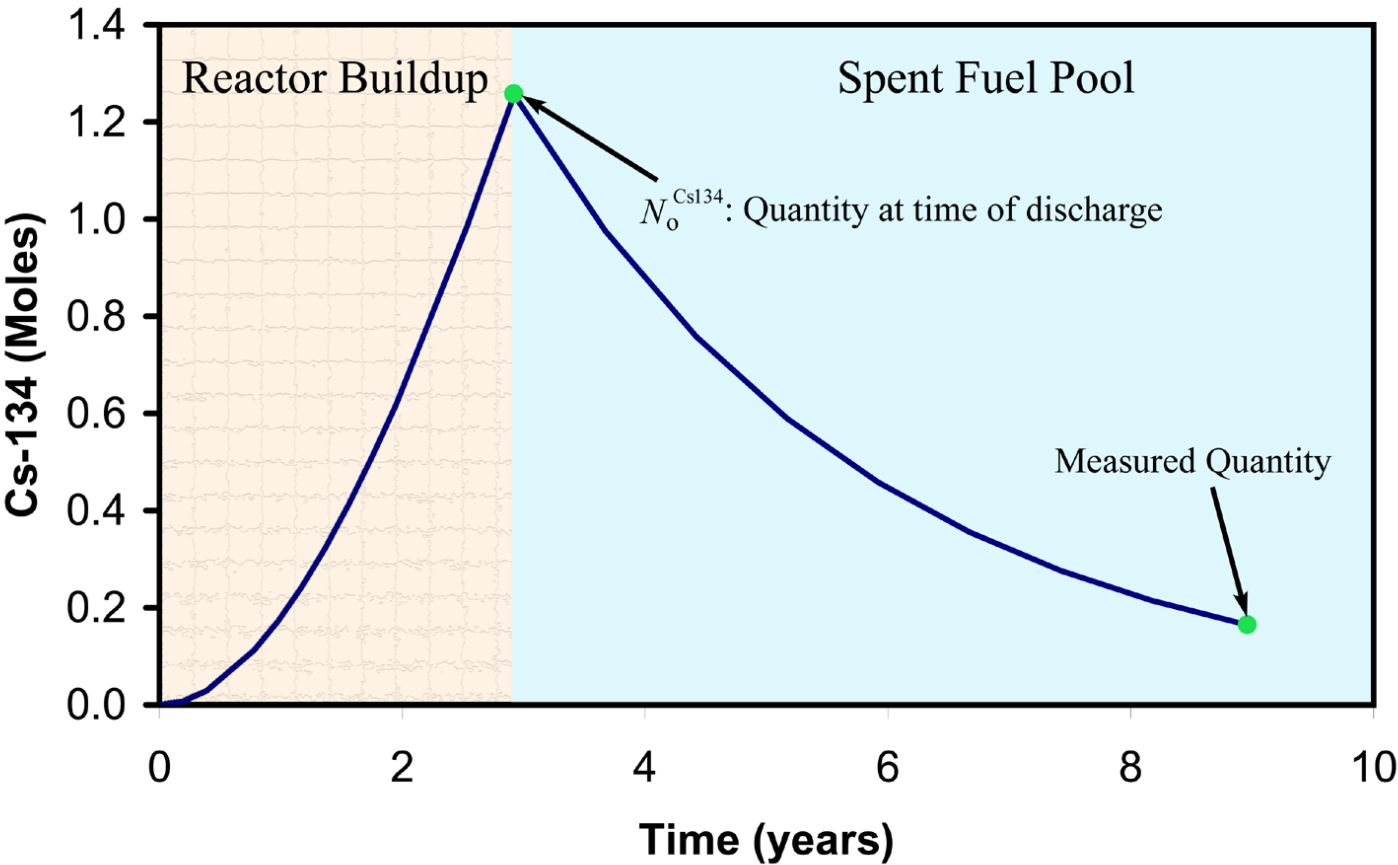
# Forensic Process for Spent Fuel



# Nuclide Production as a Burnup Indicator



# Fuel Age or Cooling Time



# Los Alamos National Laboratory

Employees: 13,137

Students: 1,323

Post docs: 498

- 65% male, 35% female
- 45% minorities
- 67% university degrees
- 27% undergraduate degrees
- 19% master's degrees
- 21% PhD



# Questions